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The CALorimetric Electron Telescope (CALET) on the International Space Station: Results from the First Two Years On Orbit

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Abstract. The CALorimetric Electron Telescope (CALET) is a high-energy astroparticle physics space experiment installed on the International Space Station (ISS), developed and operated by Japan in collaboration with Italy and the United States. The CALET mission goals include the investigation of possible nearby sources of high-energy electrons, of the details of galactic particle acceleration and propagation, and of potential signatures of dark matter. CALET measures the cosmic-ray electron+positron flux up to 20 TeV, gamma-rays up to 10 TeV, and nuclei with $Z=1$ to 40 up to 1,000 TeV for the more abundant elements during a long-term observation aboard the ISS. Starting science operation in mid-October 2015, CALET performed continuous observation without major interruption with close to 20 million triggered events over 10 GeV per month. Based on the data taken during the first two-years, we present an overview of CALET observations: 1) Electron+positron energy spectrum, 2) Nuclei analysis, 3) Gamma-ray observation including a characterization of on-orbit performance. Results of the electromagnetic counterpart search for LIGO/Virgo gravitational wave events are discussed as well.

1. Introduction

The CALorimetric Electron Telescope (CALET) [1, 2] is a high-energy astroparticle physics mission on the ISS, with development and operation conducted by Japan in collaboration with Italy and the United States. The detector was launched to orbit aboard the unmanned H2

Transfer Vehicle (HTV) atop the Japanese H2-B carrier rocket on August 19, 2015. After arrival of the HTV at the ISS, it was installed on the Japanese Experiment Module–Exposed Facility (JEM-EF). The initial mission duration was two years, extendable to five years or more. The image in Fig. 1 shows the JEM with CALET attached at port #9 of the JEM-EF, which features a mostly unobstructed field-of-view of 45° from zenith. The schematic drawing in Fig. 1 gives an overview of the CALET payload.

CALET's main instrument is a very thick calorimeter incorporating imaging and total absorption calorimeters. The overall thickness of CALET for normal incidence angle is 30 radiation length, corresponding to ~ 1.3 proton interaction length. Installed on the ISS, CALET carries out long term observation with a large area detector, thus providing a high-statistics measurement. CALET is designed to discover signatures of nearby cosmic-ray accelerators and potentially dark matter in the all-electron (electron+positron) spectrum, which is measured with high precision over a wide energy range from 1 GeV to 20 TeV, as well as in the gamma-ray spectrum measured up to 10 TeV. Protons, helium, and heavier nuclei through iron, are the main components of cosmic rays, and can be measured in the range to a PeV. The detailed mechanism and parameters governing propagation and acceleration of the galactic cosmic-rays will be investigated based on nuclei spectra measurements. CALET is expected to extend the limits of direct measurements.

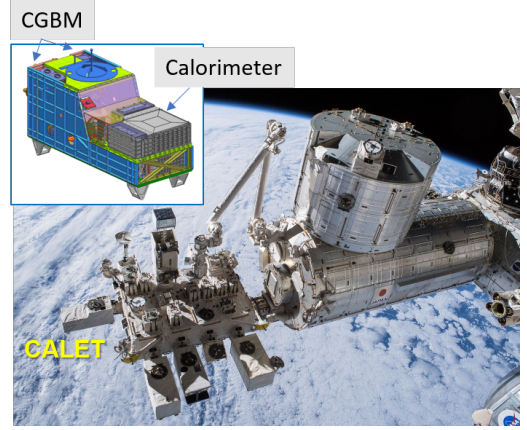


Figure 1. JEM-EF and the CALET payload attached at the port #9. The inset is the CALET instrument package showing the main calorimeter and CALET Gamma-ray Burst Monitor (CGBM) sub-systems [3].

2. Instrument

The CALET calorimeter (see the right-hand panel of Fig. 2) consists of a Charge Detector (CHD), which identifies the charge of the incident particle [4, 5], an IMaging Calorimeter (IMC), which reconstructs the track of the incident particle and records the initial shower development with fine resolution, and a Total AbSorption Calorimeter (TASC), which absorbs the entire energy of the incoming particle and identifies the particle species using hodoscopic lead-tungstate crystal arrays. The components and read-out sensors are summarized in the left panels of Fig. 2.

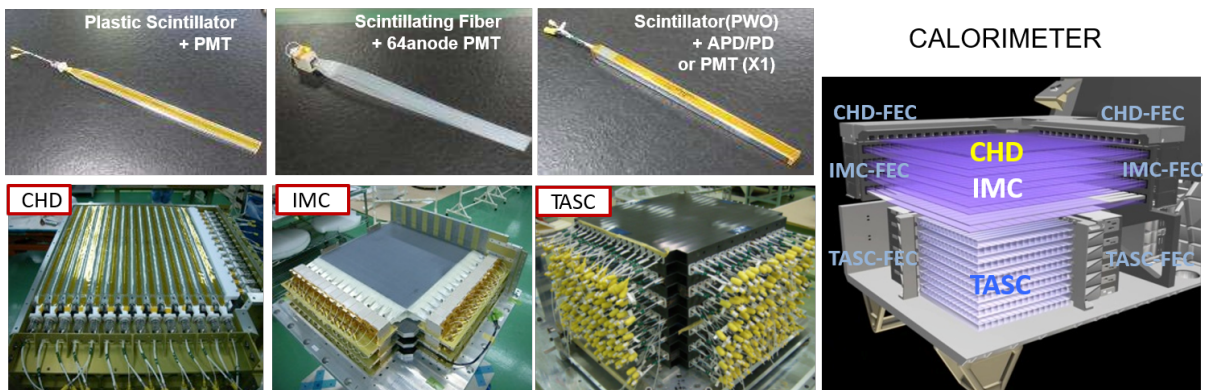


Figure 2. CALET calorimeter consisting of three sub detectors, i.e., a CHarge Detector (CHD), an IMaging Calorimeter (IMC), and Total AbSorption Calorimeter (TASC).

Combining these sub-detectors as well as the trigger system and data acquisition system, the CALET instrument features (1) a proton rejection factor larger than 10^5 , (2) a 2% energy resolution above 20 GeV for electrons, (3) very wide dynamic range from 1 GeV to 1 PeV, (4) charge resolution of 0.1–0.3 electron charge unit from protons to above iron (up to $Z = 40$), (5) an angular resolution of 0.1 to 0.5° , and (6) a geometrical factor of the order of 0.1 m²sr.

Figure 3 summarizes the CALET capability of particle identification. Top left, top right, bottom left, and bottom right panels show 3 TeV electron candidate, proton candidate with equivalent shower energy, iron candidate with shower energy of 9.3 TeV, gamma-ray candidate with 44 GeV reconstructed energy, respectively. The calorimeter with 30 radiation-length on-axis thickness absorbs the full electron shower energy even in the TeV range. Charge measurement using CHD and IMC separates each of the elements from $Z = 1$ to 26 and above. Gamma-rays are identified as charge zero because they do not produce any signal before the pair creation. While both of electrons and protons have $Z = 1$, they can be separated using the differences in their shower shapes. Because of the continuing showering activity in the lower part of the TASC due to subsequent interactions of secondary pions, electrons, and protons are easily separated by a simple cut even in the TeV region. In addition to this, various parameters characterizing the shower shape can be utilized to improve the separation power [6, 7].

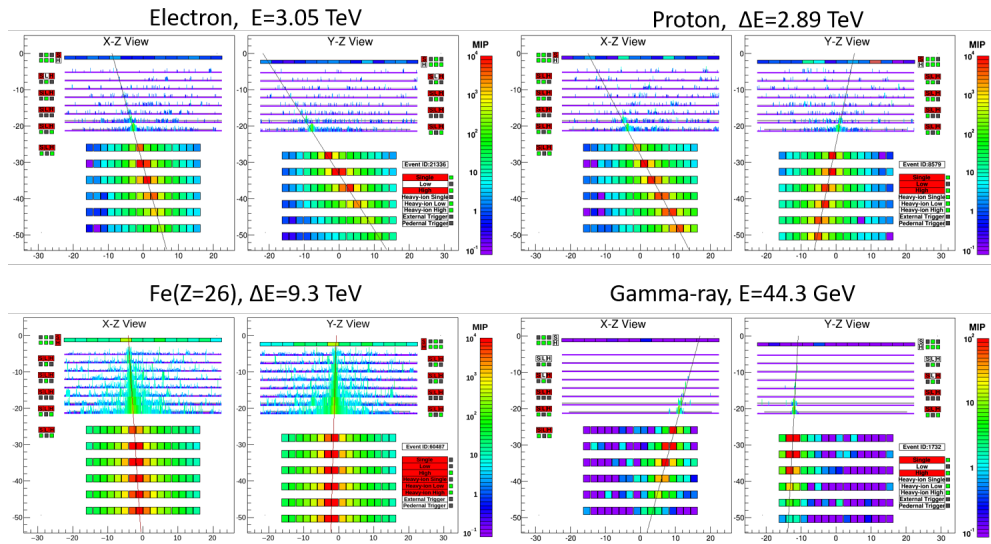


Figure 3. Event examples of high-energy showers collected by CALET onboard the ISS. (*Top Left*) a 3 TeV electron candidate, (*Top Right*) a proton candidate with equivalent shower energy, (*Bottom Left*) an iron candidate with shower energy of 9.3 TeV, and (*Bottom Right*) a 44 GeV gamma-ray candidate.

3. On-Orbit Operations

For on-orbit operation of CALET, JAXA Ground Support Equipment (JAXA-GSE) and the Waseda CALET Operations Center (WCOC) were set up at Tsukuba Space Center and Waseda University, respectively. The data taken by the CALET instrument are transferred from the ISS to JAXA using NASA's data relay system. The scientific operations of CALET are planned at WCOC [8] based for example on the variation of the geomagnetic rigidity cutoff depending on ISS position. Accordingly is the observation mode of CALET controlled by scheduled command sequences. These sequences define the time profile of calibration and data acquisition tasks as for example the recording pedestal and penetrating particle events, as well as switching on/off observation modes such as a

low-energy electron trigger operating at high geomagnetic latitude, a low-energy gamma-ray (LE- γ) trigger operating at low geomagnetic latitude, and an almost continuously active ultra heavy trigger mode, during each ISS orbit. Maximum exposure to high-energy electrons and other high-energy shower events is ensured by an always active high-energy (HE) trigger mode.

As of May 31, 2018, the total observation time is 962 days with a live time fraction of $\sim 84\%$ relative to the total time. Close to 630 million events were taken with the HE ($E > 10$ GeV) trigger mode. Figure 4 shows the accumulated live time for the HE trigger. Cumulative observation time has increased without significant interruption since scientific operation start in October 2015. Data transmission from JAXA-GSE to WCOC and data processing for scientific analysis at WCOC also proceeded smoothly.

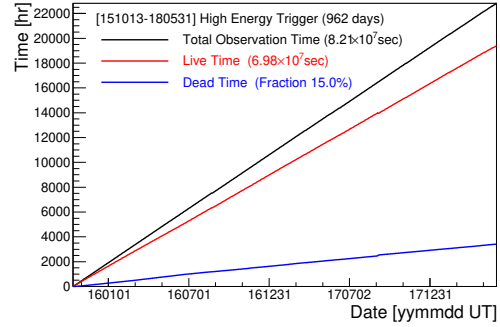


Figure 4. Cumulative of observation time (black line) for HE trigger. The red and blue lines indicate the live and dead times, respectively.

4. Calibration

Energy calibration is a key procedure for CALET as a calorimeter instrument to achieve high precision and accurate measurements. While excellent energy resolution inside the TeV region is one of the most important features of a thick calorimeter instrument like CALET, calibration errors must be carefully assessed and taken into account in the estimation of the actual energy resolution.

Our energy calibration [9] includes the evaluation of the conversion factors between ADC units and energy deposits, ensuring linearity over each gain range (TASC has four gain ranges for each channel), and provides a seamless transition between neighboring gain ranges. Temporal gain variations occurring during long time observations are also corrected for by the calibration procedure [6].

The errors at each calibration step, such as the correction of position and temperature dependence, consistency between energy deposit peaks of non-interacting protons and helium, linear fit error of each gain range, and gain ratio measurements, as well as slope extrapolation, are included in the estimation of the energy resolution.

As a result, a very high resolution of 2% or better is achieved above 20 GeV [9] as shown in the top panel of Fig. 5. It should be noted that even with such a detailed calibration, the determining factor for the energy resolution is the calibration uncertainty, as the intrinsic resolution of CALET is $\sim 1\%$. Intrinsic resolution refers to the detector's capability by design, taking advantage of the thick, fully-active total absorption calorimeter. Also important is the fact that the calibration error in the lower gain ranges is crucial for the spectrum measurements in the TeV range.

The bottom panel of Fig. 5 shows the TASC energy deposit spectrum using all triggered

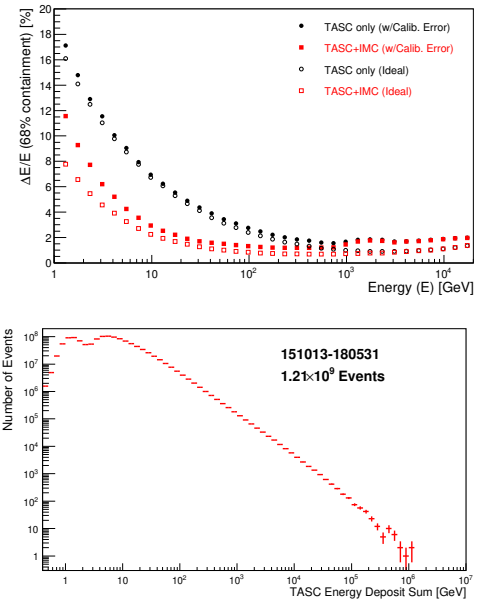


Figure 5. (Top) Energy resolution for electron measurements [9], (Bottom) TASC energy deposit spectrum using all triggered events up to May, 2018.

events through the end of May, 2018. The first bump is due to low-energy triggered events, while the second bump is caused by high-energy triggered events and the tail at high energy reflects the power-law nature of the cosmic-ray spectrum. The spectrum spans more than six orders of magnitude in energy with highest energy past a PeV, and the lowest energy below 1 GeV. This clearly demonstrates the CALET capability to observe cosmic rays over a very wide dynamic range.

5. Results

5.1. All-Electron Spectrum

A precise measurement of the all-electron (electron + positron) spectrum in the TeV region might reveal interesting spectral features to provide the first experimental evidence of the presence of a nearby cosmic-ray source [10, 11]. In addition, the unexpected increase of the positron fraction above 10 GeV established by PAMELA [12] and AMS-02 [13] may require a primary source component for positrons in addition to the generally accepted secondary origin. Candidates for such primary sources range from astrophysical (pulsar) to exotic (dark matter). Since these primary sources emit electron-positron pairs, it is expected that the all-electron spectrum would exhibit a spectral feature, near the highest energy range of the primary component.

The CALET collaboration published its first result on electrons in the energy range from 10 GeV to 3 TeV [6]. Subsequently, the DArk Matter Particle Explorer (DAMPE) collaboration published their all-electron spectrum in the energy range from 25 GeV to 4.6 TeV [14]. The latter publication was followed by many papers speculating about the origin of a peak-like structure near 1.4 TeV in the DAMPE data.

Recently, an updated version of the CALET all-electron spectrum using 780 days of flight data and the full geometrical acceptance was published in the energy range from 11 GeV to 4.8 TeV [7]. Figure 6 shows the updated all-electron spectrum obtained with CALET using the same energy binning as in our previous publication [6], except for adding one extra bin at the high energy end. The error bars along horizontal and vertical axes indicate bin width and statistical errors, respectively. The gray band is representative of the quadratic sum of statistic and systematic errors. The exhaustive study on the systematic uncertainties was performed and is described in Refs. [6, 7] including their Supplemental Materials.

There are four important implications from the current status on the all-electron spectrum measurements. First, CALET's spectrum is consistent with AMS-02 below 1 TeV. As both detectors have enough capability to identify electrons up to 1 TeV, and the detection principles are largely different (calorimeter versus magnet spectrometer), the agreement is an important indication. Secondly, there are two group of measurements: AMS-02 + CALET vs Fermi-LAT + DAMPE, indicating the presence of unknown systematic errors. Thirdly, CALET observes flux suppression consistent with DAMPE within errors above 1 TeV. No peak-like structure was found at 1.4 TeV in CALET data, irrespective of energy binning as shown in Fig. 7.

In the left-hand plot of Fig. 7, we have adopted exactly the same energy binning as DAMPE to show our spectrum. The flux is inconsistent between the two experiments with a 4σ significance; the CALET data does not show any significant excess in the 1.4 TeV bin. The significance includes the systematic errors quoted from both experiments. Furthermore, possible binning related effects in the CALET all-electron spectrum are studied with a shift of one fourth of the bin width as shown in the right-hand plot of Fig. 7. The solid curves in the figure show the energy dependent systematic uncertainty band. The deviation due to binning is well below our energy dependent systematic uncertainty or statistical fluctuations. Therefore, bin-to-bin migration and related effects are negligible compared to our estimated systematic uncertainties, in accordance with the estimated CALET energy resolution of 2% above 20 GeV.

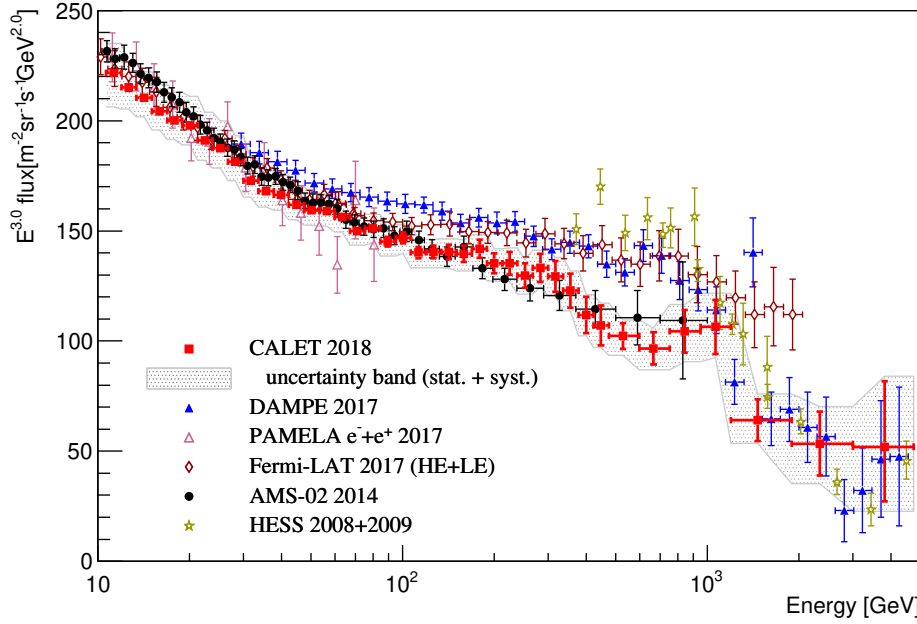


Figure 6. Cosmic-ray all-electron spectrum measured by CALET from 10.6 GeV to 4.75 TeV [7], where the gray band indicates the quadratic sum of statistical and systematic errors (not including the uncertainty on the energy scale). Also plotted are direct measurements in space [14, 15, 16, 17] and from ground-based experiments [18, 19].

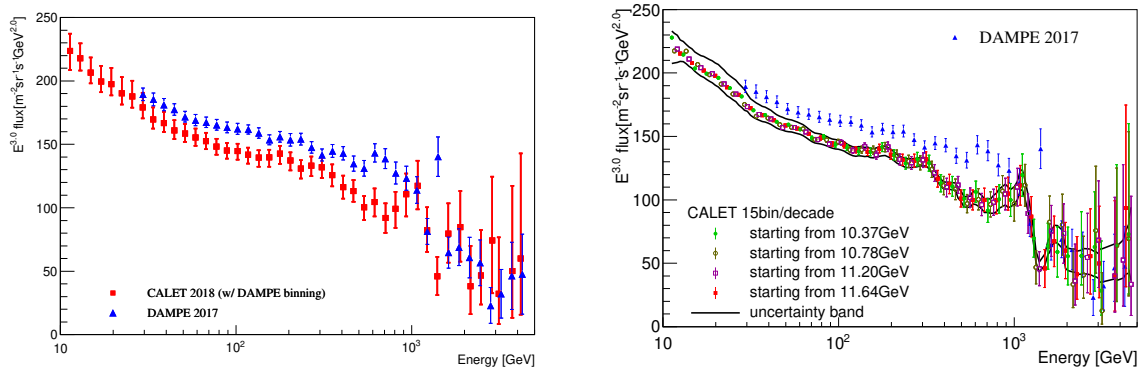


Figure 7. (Left) Cosmic-ray all-electron spectrum measured by CALET from 10.6 GeV to 4.57 TeV [7], using the same energy binning as DAMPE's result [14] and compared with it. The error bars indicate the quadratic sum of statistical and systematic errors. (Right) Study of possible binning related effects in the CALET all-electron spectrum [7].

5.2. Hadrons

Direct measurements of the high-energy spectra of each species of cosmic-ray nuclei up to the PeV energy scale provide information complementing all-electron observations and provides more detailed insight into the general conditions of cosmic-ray acceleration and propagation. A possibly charge-dependent cutoff in the nuclei spectra is hypothesized to explain the “knee” in the all-particle spectrum. This hypothesis could only be investigated by a space experiment with sufficient exposure. The acceleration limit of supernova remnants calculated with nominal parameters is typically found to be far smaller than the energy of the “knee” [20] observed indirectly by ground detectors. Therefore, precise direct observation of the proton and helium spectra up to PeV energy is highly important. Also the spectral hardening observed in spectra of various nuclei calls for a careful investigation, with CALET's wide dynamic range from GeV

to PeV energies allowing to study the feature unaffected by systematics from combination of spectra measured by different experiments. Another detailed study will be done on the spectral behavior of heavier elements, including secondary-to-primary ratios up to 1 TeV/n energy region, which should yield important information about propagation parameters such as the diffusion coefficient.

Figure 8 illustrates the charge identification capability of CALET based on the CHD data only, showing clear separation of protons, helium and nuclei up to iron and nickel. The IMC provides an independent and about equally powerful charge separation capability for light elements. Until now preliminary results on protons [21] and heavier nuclei [22, 23] have been presented, taking advantage of the accurate charge determination and wide energy range. The first results on the nuclei spectra will be published soon, including a detailed assessment of systematic uncertainties.

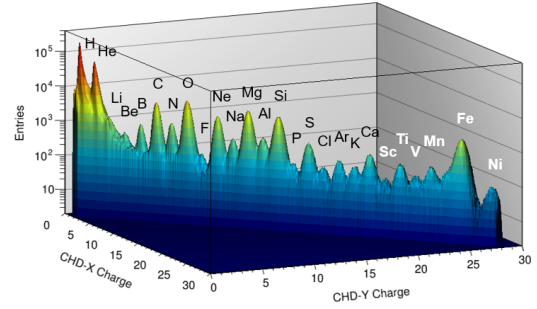


Figure 8. CHD charge separation.

5.3. Gamma-Rays

With a fully active 30 radiation-length thick calorimeter, CALET is capable of measuring gamma-rays up to the TeV region. In addition to HE trigger, CALET uses LE- γ trigger to be sensitive to gamma rays with primary energies down to 1 GeV. To avoid large dead-time fraction, however, LE- γ trigger is activated only at low geomagnetic latitudes or following gamma-ray burst triggered onboard by CALET gamma-ray burst monitor (CGBM).

The first 24 months of on-orbit scientific data provide valuable characterization of the performance of the calorimeter based on the analyses of the gamma-ray data set [24]. It includes optimization of event selection criteria, calculation of effective area, determination of point spread function, confirmation of absolute pointing accuracy, observation of bright point sources and study of diffuse components. Based on the developed analysis method, CALET gamma-ray sky seen by LE- γ trigger is shown in the left-hand panel of Fig. 9, where galactic emission and bright gamma-ray sources are clearly identified. In the right-hand panel of Fig 9, projection of the observed and expected number of photons onto galactic latitude for the galactic plane region $|l| < 80^\circ$ is shown. Expected number of photons are calculated using Fermi/LAT flux map and CALET's exposure in the same region of the sky. The very good consistency confirmed our sensitivity. It should be noted, that it is important to take the effects of ISS structures in the field-of-view into account.

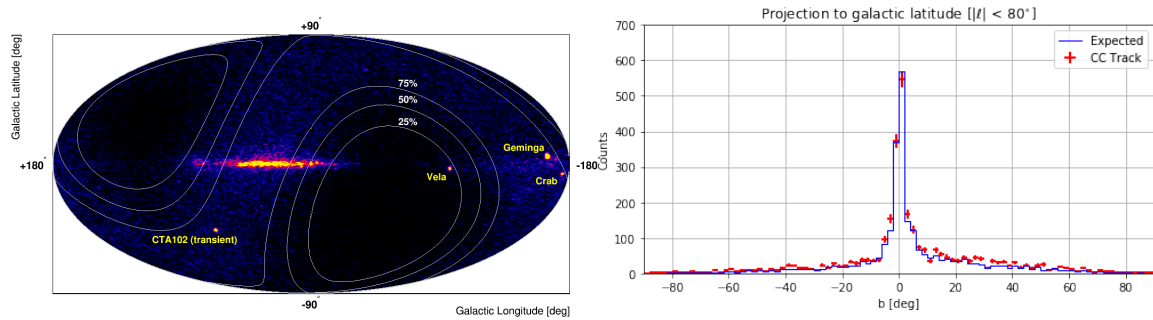


Figure 9. (Left) Gamma-ray sky map shown in a Mollweide projection of galactic coordinates. White contours show the relative level of exposure compared to the maximum on the sky. (Right) Projection of the observed and expected number of photons onto galactic latitude for the galactic plane region $|l| < 80^\circ$ for the energy range from 1 to 100 GeV.

Gamma-ray transients are also an important observational target for CALET. CGBM detected nearly 60 GRBs ($\sim 20\%$ short GRB among them) per year in the energy range of 7 keV–20 MeV, as expected [25]. To search for GeV-energy counterpart emission from such sources also detected by other instruments, we check the CAL data at the reported trigger times for gamma-ray candidates. For events checked based on CGBM, Swift, and Fermi/GBM triggers, no significant counterparts have been detected at this stage for timescales ranging from 1 s to 1 hr [24]. Regarding the counterpart search for gravitational wave events, combined analyses of CGBM and calorimeter were performed for GW151226, resulting in our upper limits set on X-ray and gamma-ray counterparts [26]. Furthermore, complete search results of CALET calorimeter on the LIGO/Virgo's Observation Run 2 has been published recently [27].

6. Summary and Prospects

CALET was successfully launched on Aug. 19, 2015, and detector performance for scientific observation has been continuously very stable since Oct. 13, 2015. Careful calibrations using “MIP” signals of the non-interacting protons and helium events have been successfully carried out, and the linearity of the energy measurements up to 10^6 MIPs was established based on observed events [8, 9].

The all-electron spectrum [6] has been published with extended energy range from 11 GeV to 4.8 TeV [7] and improved statistics. Figure 10 presents the current situation of all-electron spectrum direct measurements in space. Five years or more of observations with CALET will triple the statistics, which together with a reduction of systematic errors based on a better understanding of the detector with an increased amount of the flight data will lead to significantly improved precision. This will allow a refined study of the possible fine structures around a few hundred GeV and ~ 1 TeV, which are currently not significant, which might shed light on the origin of the positron excess. An extension of the high-energy reach using improved statistics and electron separation methods might for the first time reveal a charged cosmic-ray signature of a local accelerator.

Preliminary results on protons [21], primary and secondary nuclei up to $Z = 26$ and their ratios (for example, boron to carbon) [22, 23] were presented so far, demonstrating CALET's wide dynamic range of energy measurement from 1 GeV to 1 PeV and the accuracy of its charge determination capability. Their publication is foreseen in the near future, and will address important questions in cosmic-ray physics, such as the charge dependence of the acceleration limit in supernova remnants, the universality of the widely observed spectral hardening, and the energy dependence of the diffusion coefficient. The relative abundance of the ultra heavy nuclei up to $Z = 40$ is also analyzed [28].

There is also significant progress in CALET's gamma-ray analysis. Based on the science data taken in two years on orbit, the performance of the gamma-ray measurements has been characterized [24]. These results confirm the capability of CALET to observe gamma rays in the energy range from ~ 1 GeV to over 100 GeV. CALET's current results on electromagnetic counterpart search for gravitational wave events [26, 27] show the great potential of follow-up

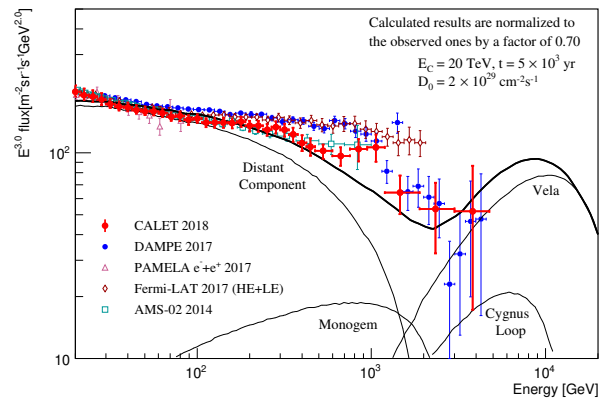


Figure 10. Current situation of all-electron spectrum directly measured in space, together with the model calculation [11], where main model parameters are shown in the plot.

observations during the upcoming LIGO/Virgo's third observation run (Observation Run 3). The continuous GeV gamma-ray sky observation with CALET complements the coverage by other missions and may help to identify unexplored high-energy emissions from future transient events. Watching for various transient phenomena including those in gamma rays, but not limited to them is an important task for CALET as an on-orbit observation strategy. Through the detection of many events of MeV electrons originating from the radiation belt [29], a phenomenon called relativistic electron precipitation, space weather was added as an additional observational target for CALET after the start of on-orbit operations.

The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year (or more) observation period will most likely provide a wealth of interesting new results.

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